



University
of Glasgow

HIGH FREQUENCY COMMUNICATION SYSTEMS

Lecture 10

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Spring 2022

- mmWave Communications]
- mmWave Antennas
- mmWave Beamforming Algorithms

MMWAVE COMMUNICATIONS

(BW) $\uparrow \rightarrow f \uparrow$ $BW \propto f$

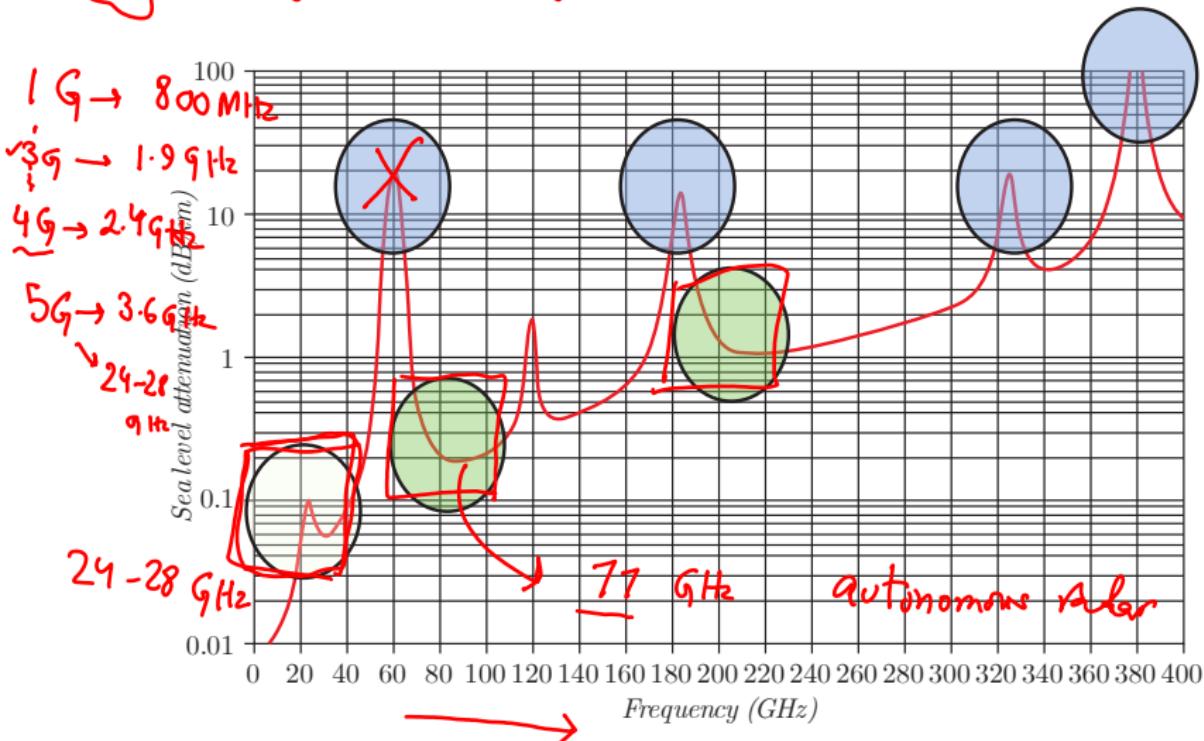


Figure 1: EM wave attenuation due to O_2 molecules in air in the mmWave spectrum. [T. S. Rappaport et al, Proceedings of the IEEE, vol. 99, no. 8, pp. 1390-1436, 2011.]



absorb mmWaves

- [] · λ at mmWave becomes so small that the O_2 and H_2O molecules in the air severely affect the wave propagation
- Besides this, we have the effects of weather such as rain, fog etc.
 - The wave is also attenuated due to distance and other obstacles
- { We need to design antennas that perform effective communications.

- mmWave signals have extremely short wavelengths ($\lambda = 10.7 \text{ mm at } 28 \text{ GHz}$, $\lambda = 5 \text{ mm at } 60 \text{ GHz}$)
- As a result, objects that would scatter EM waves may now act as *reflectors*.
- Significantly higher multipath effects at mmWave as compared to microwave systems
- These small dimensions enable extremely integrated and physically small antennas
 - In-package and on-chip antennas
 - We can make the antennas with the same fabrication process as the rest of the IC

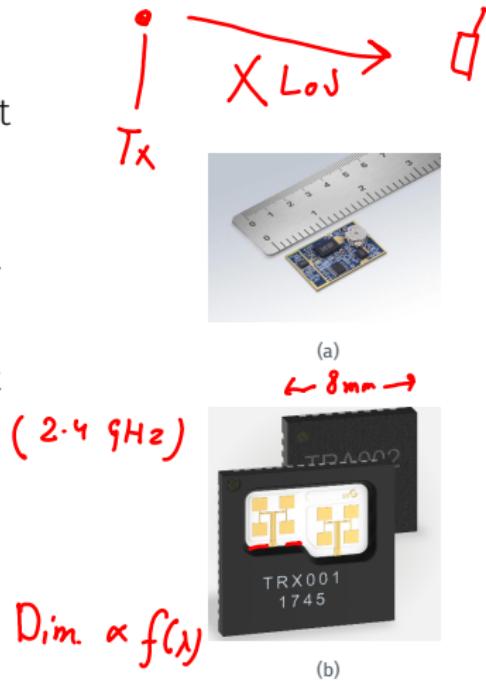


Figure 2: An on-chip 3 GHz to 5 GHz and a 120 GHz antenna in package (8 mm by 8 mm) (©NXP Semiconductors, Silicon Radar).

- The wave propagation can be modelled macroscopically (large-scale channel effects) or microscopically (small-scale channel effects)
- Lets start with the *Friis transmission equation*:

$$P_{Rx} = \left[P_{Tx} \text{Gain}_{Tx} \text{Gain}_{Rx} \text{Loss Factor} \right] \left(\frac{\lambda}{4\pi D} \right)^2$$

•

	$f_c = 460 \text{ MHz}$	$f_c = 2.4 \text{ GHz}$	$f_c = 5 \text{ GHz}$	$f_c = 60 \text{ GHz}$
$d = 1 \text{ m}$	-25.7 dB	-40 dB	-46.4 dB	-68 dB
$d = 10 \text{ m}$	-45.7 dB	-60 dB	-66.4 dB	-88 dB
$d = 100 \text{ m}$	-65.7 dB	-80 dB	-86.4 dB	-108 dB
$d = 1,000 \text{ m}$	-85.7 dB	-100 dB	-106.4 dB	-128 dB

Figure 3: Free space Path Loss at different frequencies.

From previous lectures, the antenna gain is:

$$\text{Gain}_{\max} = e_{\max} A_{\max} \frac{4\pi}{\lambda^2}$$

We typically treat $A_{\max} \propto D^2$. For a uniform linear array of N elements,

$$D_{\text{array}} = N \times D_{\text{element}}$$

For a two-dimensional array, the gain therefore, becomes even higher,

$$\text{Gain}_{\max} \propto \frac{4\pi D_{\text{array}}^2}{\lambda^2}$$

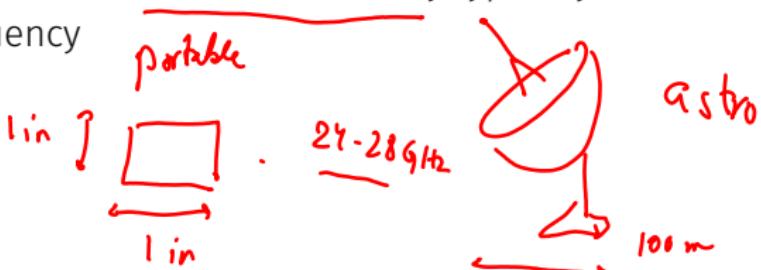
$$\left\{ P_{\text{Rx}} = \frac{P_{\text{Tx}} e_{\text{Tx}}^- e_{\text{Rx}}^- (D_{\text{Rx}} D_{\text{Tx}})^2}{L(\lambda d)^2} \right.$$

SOME IMPORTANT OBSERVATIONS



: 1
.: 1

- As frequency increases, we can stack more antenna elements in an array within a given size
 - Results in increased gain $\boxed{N \times E_{\text{elements}}}$
 - The Tx and Rx antennas become highly directional
 - The steering of the beams becomes an altogether new topic of research
 - The path loss can be overcome $\propto \frac{1}{d^2}$
- For a given gain, the effective area is proportional to $1/f^2$
 - However, the antenna efficiency typically decreases as we go up in frequency



According to the famous *Shannon capacity* theorem, a wireless channel capacity, C for a signal with power P is,

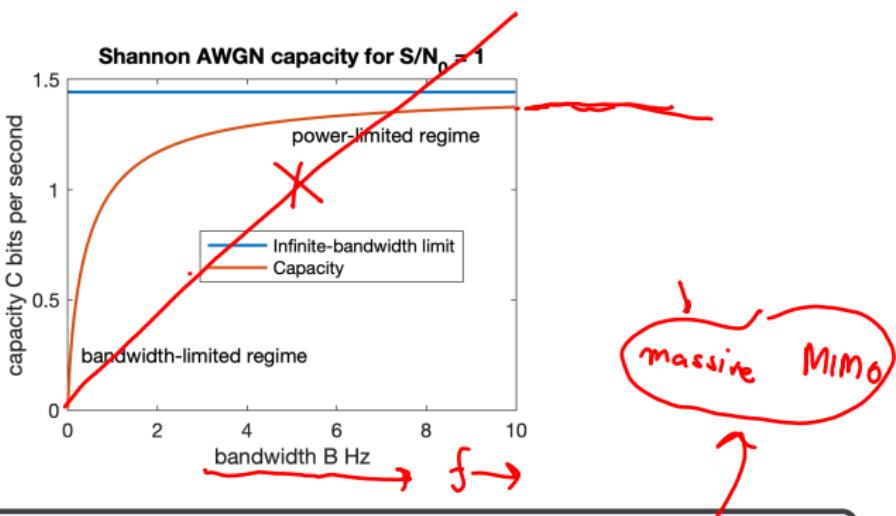
$$\cdot \quad C = \underbrace{BW}_{\text{Bandwidth}} \log_2 \left(1 + \frac{\underbrace{P}_{\text{Power}}}{\underbrace{BW N_0}_{\text{Noise spectral density}}} \right)$$

where, BW is the signal bandwidth, and N_0 is the noise spectral density.

- For a given power $\underbrace{P_0}_{\text{Power}}$, the capacity is an increasing function of $\underbrace{BW}_{\text{Bandwidth}}$.
- However, we approach a limit,

$$\left[\lim_{BW \rightarrow \infty} BW \log_2 \left(1 + \frac{P_0}{BW N_0} \right) = \frac{P_0}{\log(2)N_0} \right]$$

We can only ever get some bandwidth benefits out of a mmWave system.



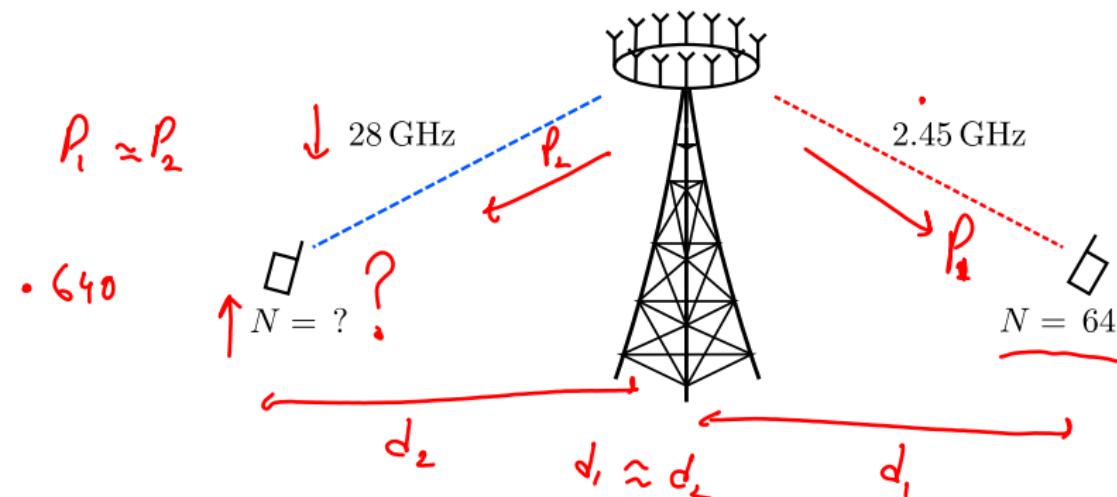
{ For mmWave systems, we need to increase the power (*gain*) to get a similar network performance.

EXAMPLE - FINDING THE NUMBER OF ANTENNAS

C P_{Rx}

Consider, we want to have the same quality of service (i.e., same link budget) in the scenario below. What is the approximate number of antenna elements required in the mmWave case?

Treat the antennas as ideal with the distance from the transmitter and similar efficiencies.



From the *Friis formula*, we can estimate the link budget. We would like to have the same power received in both cases.

An approximate value, discounting the efficiencies, interference, and noise can be written as:

$$N_2 \approx \left(\frac{f_2}{f_1}\right)^2 N_1$$

$$P_{r_1} = \dots \frac{N_1}{\lambda_1^2}$$

$$P_{r_2} = \frac{N_2}{\lambda_2^2}$$

$N_2 \approx 136.11 \times 64$

We need ≈ 136 times more antennas to maintain the link budget!

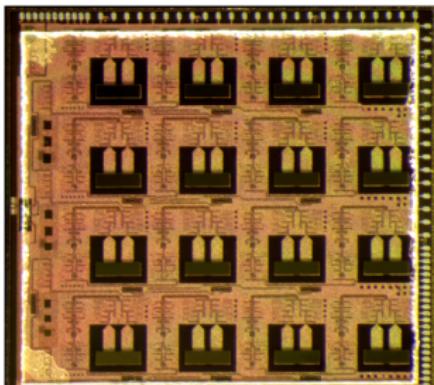
64×136 ? outrageously high
 feeding network

MMWAVE ANTENNAS

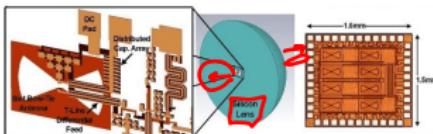
- So far, we have considered an ideal scenario where we ignored all the factors that affect antenna performance
 - In reality, mmWave antennas are in-efficient
 - Feeding networks become complex due to the large number of array elements
- With good designs, we can achieve antenna efficiency up to 80 %
- Mainly there are two types of designs, *on-chip* and *in-package* antennas

ON-CHIP ANTENNAS

- The biggest motivation behind the use of on-chip antennas is the low-cost and integration with the rest of electronics
- We can achieve gain up to 30 dB and antenna efficiency over 85 %
- There are four design challenges that one has to consider
 - Generation of surface waves → *coupling X*
 - Direction of antenna radiation
 - Substrate loss
 - Resonant frequency of the substrate
- As the antenna may be surrounded by nearby metal vias, we need to consider coupling effects.



(a)



(b)

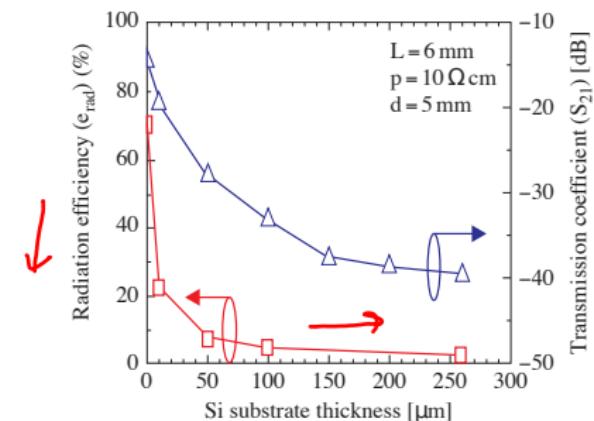
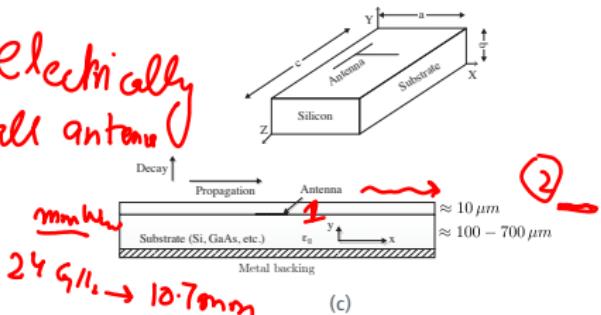
- The nature of the structure supports the unwanted generation and radiation of surface waves
- Surface waves travel along the axis of the substrate
 - They reduce the efficiency
 - Increase the coupling between adjacent structures

As a remedy, we can increase the substrate thickness to suppress the surface waves

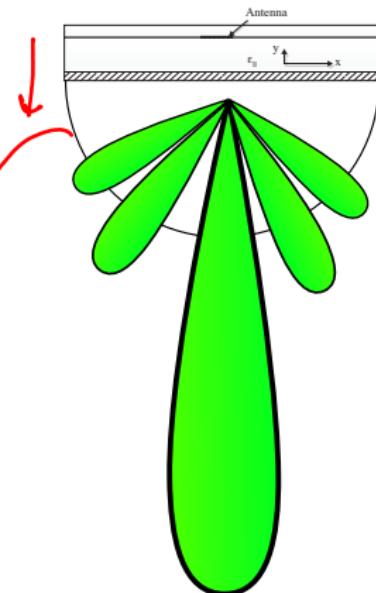
- However, this has detrimental consequences on antenna efficiency

$$L < \lambda_0/10$$

Electrically small antenna



- Due to the high dielectric permittivity of Si ($\epsilon = 11.7$), the direction of radiation is **into** the substrate rather than out.
- Moreover, the waves get attenuated in the substrate before they can leave the structure
- **Hemispherical dielectric lenses** are used to **focus** the waves before they radiate from the structure.

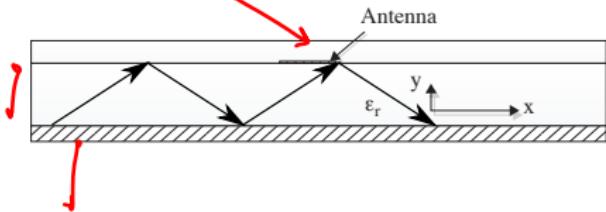


Si \rightarrow 11.7

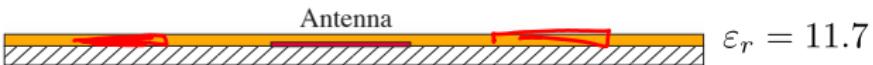
GaN \rightarrow 9.6

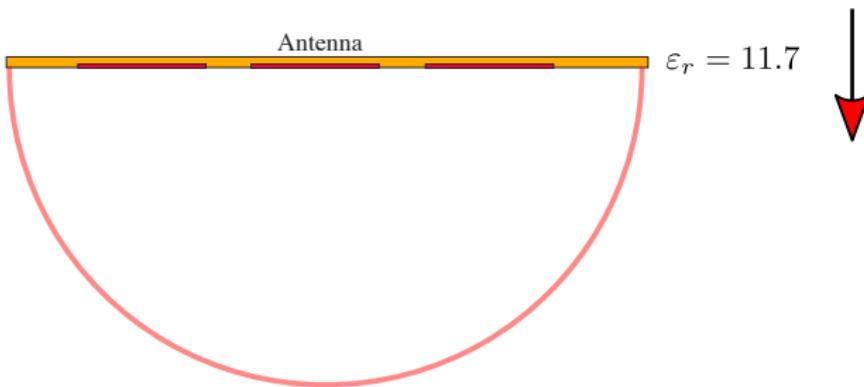
multilayer

- The presence of metal vias
- Lower permittivity substrates should be used to avoid the generation of surface waves.
- Most of the waves actually get trapped and therefore attenuated to the low critical angle of Si ($\arcsin 1/\sqrt{\epsilon_{r,sub}}$)



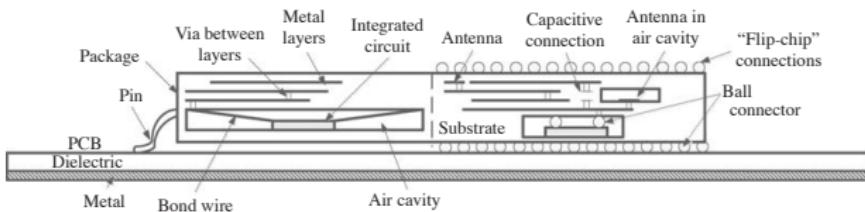
Li is an antenna designer and needs to decide the best material as well as the topology of the antenna that will be *integrated* with a CMOS circuit. The current design is giving her a poor radiation efficiency of 30 %. Suggest some improvements to increase the antenna performance.



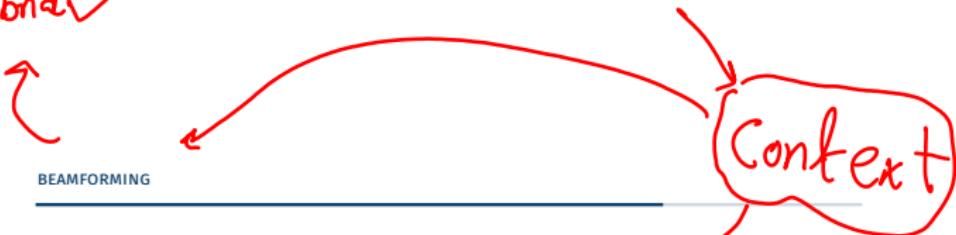


lower BW

- An in-package antenna consists of several co-planar metal layers
- It is manufactured using a packaging process
- Connections within the layers are made through vias
- Due to better isolation, we can get better antenna performance compared to on-chip antennas
- Antenna is created through an air cavity → *high resonance ↑ radiation efficiency*
- Design requires a careful selection of permittivity of the substrate
- Scaled microwave designs are used to fabricate antennas

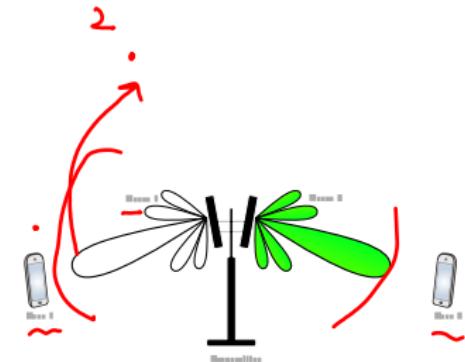


analog → NT very high X
digital →
by brid✓



very complicated
& complex feeding network

- [Need to combat multipath fading]
- [Increase signal to noise ratio]
- [Decrease interference between users]
- We typically rely on antenna diversity
 - More antennas, more power at the receiver
- [We treat beamforming as an optimisation problem]

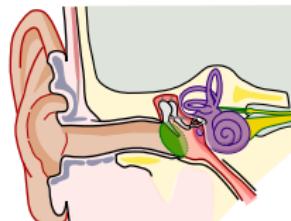


- For beamforming, determining the direction of an incoming signal through the direction of arrival (DoA) algorithms is a key element.
- The goal is to develop a machine like the human ear
- DoA or direction finding algorithms reconstruct the signals from each direction and try to determine the identity of the signal source.

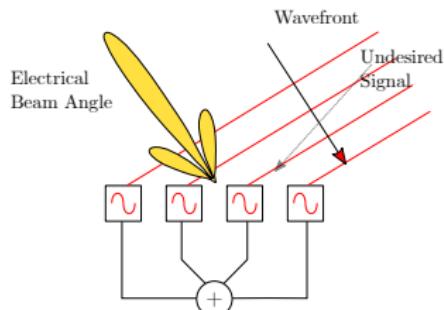
Correlation

$$S_i = \sum_{\ell=1}^N m_{\ell}(t) e^{-j\vec{k}_{\ell} \cdot (\vec{r}_i - \vec{r}_1)}$$

here \vec{k}_{ℓ} is the wave-vector, \vec{r}_1 and \vec{r}_i are the positions of the reference and i-th array elements.



(e)



Phase-delayed antenna elements

(f)

We seek to construct a matrix, \mathbf{X} for an array of M elements with N snapshots recorded in time.

$$\mathbf{X} = \begin{bmatrix} S_1(t_1) & \dots & S_1(t_N) \\ \dots & \dots & \dots \\ S_M(t_1) & \dots & S_M(t_N) \end{bmatrix}$$

Next, a covariance matrix \mathbf{R} needs to be estimated for the incoming signal \mathbf{X} polluted with noise N ,

$$\mathbf{R} = \left(\frac{1}{N} \right) \mathbf{X}^* \mathbf{X}$$

We also need to *track* the directions in which the array is activated. We represent this with a steering vector,

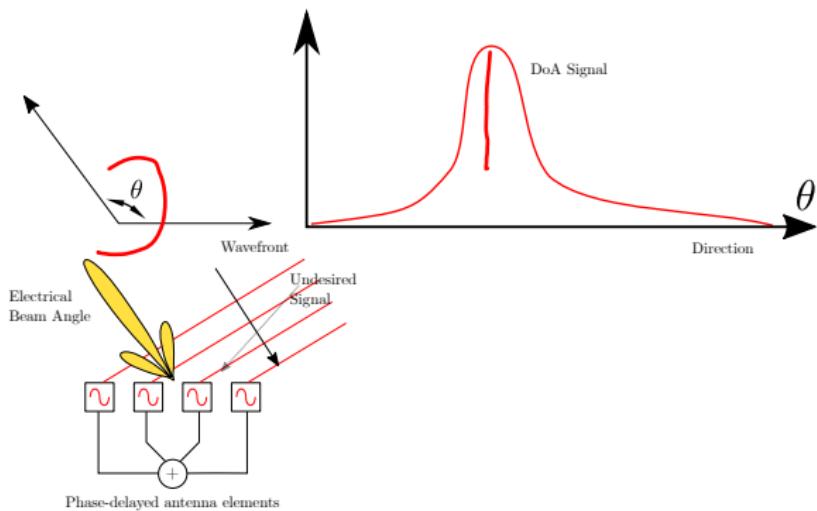
$$\mathbf{a}_{\text{direction}} = \begin{bmatrix} 1 & e^{-j \vec{k}_l \cdot (\vec{r}_1 - \vec{r}_2)} & \dots & e^{-j \vec{k}_l \cdot (\vec{r}_1 - \vec{r}_M)} \end{bmatrix}$$

The next step involves the intensive computation of weights which will be applied to each direction vector:

$$\mathbf{w} = \frac{\mathbf{R}^{-1}\mathbf{a}_{\text{direction}}}{(\mathbf{a}_{\text{direction}}^* \mathbf{R}^{-1}\mathbf{a}_{\text{direction}})}$$

- There are established ways to solve the above matrices
- Two of the most famous direction-finding algorithms are multiple signal classification (MUSIC) and estimation of signal parameters via rotational invariance techniques (ESPIRIT)
- Using some terminologies from Linear Algebra, both the algorithms above assume the covariance matrix column space is spanned by two orthogonal subspaces
 - They are signal and noise subspaces

DOA OUTPUT



- Going up in frequency not always results in higher channel capacity
- mmWave Channel constraints can be overcome by high-gain, antenna arrays
- For mmWave networks, maintaining a practical link budget requires beamforming
- mmWave antenna is a hot research topic
- High antenna efficiency

Chapter 4

T. S. Rappaport, R. W. Heath, R. C. Daniels, and J. N. Murdock,
Millimetre-wave wireless communications. Upper Saddle River, NJ:
Prentice-Hall, 2015.